CAIs in Semarkona (LL3.0).

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Introduction: Calcium, Aluminum-rich inclusions (CAIs) are the first forming solids of the Solar system. Their observed abundance, mean size, and mineralogy vary quite significantly between different groups of chondrites [1]. These differences may reflect the dynamics and distinct cosmochemical conditions present in the region(s) of the protoplanetary disk from which each type likely accreted. Only about 11 such objects have been found in L and LL type [2-4] while another 57 have been found in H type ordinary chondrites [5-6], compared to thousands in carbonaceous chondrites. At issue is whether the rare CAIs contained in ordinary chondrites truly reflect a distinct population from the inclusions commonly found in other chondrite types. Semarkona (LL3.00) (fall, ~691 g) is the most pristine chondrite available in our meteorite collection. Here we report petrography and mineralogy of 3 CAIs from Semarkona.

Analytical Methods: We have carried out a systematic search for refractory inclusions in ordinary chondrites using the NASA-JSC JEOL field emission microprobe (8530F) by rastering a focussed electron beam of 25-60 nA accelerated at 15kV and obtaining elemental abundances maps using a Thermo ultradry EDS detector [7]. The combined X-ray elemental mosaic maps (e.g., Mg/Ti-Ca-Al, Mg-Ca-Si) helped us identify 3 CAIs, 1 spinel grain, 2 Al-rich chondrules and 2 Amoeboid olivine aggregates (AOAs) in a ~135mm^2 region of thin section (#5338). Quantitative analyses of phases were done using 15kV, focused electron beam (1μm, 30nA) in the wavelength dispersive mode.

Petrology: *CAI#1:* has a chain like morphology with several nodules in close contact leading to a total length of ~60 μm (Fig. 1 A-B). Nodules vary in size from ~7-15 μm with each individual nodule consisting of ~4-8 μm of pure end-member spinel ($MgAl_2O_4$; MgO ~28-32 wt.% and Al_2O_3 ~68-72 wt.%) at the core surrounded by Ca, Al-rich diopside that grades from Ti-rich (TiO_2 ≤12 wt.%, typically 8-6 wt.%; Al_2O_3 ~36 wt.%) to Ti-poor (TiO_2 ~2 wt.%) outwards. FeO abundance in spinel is less than <0.6 wt.%. A perovskite grain of ~0.7 μm is present at the edge of spinel (Fig. 1B). There are several fine to coarse Fe-rich grains in the surrounding olivine matrix. The outer diopside layer varies in thickness and has been broken/ corroded to leave cavities between the spinel grain and outer rind of diopside surrounding nearly all of the nodules. Na_2O abundance within spinel and pyroxene are below 0.2 and 0.6 wt.%, respectively.

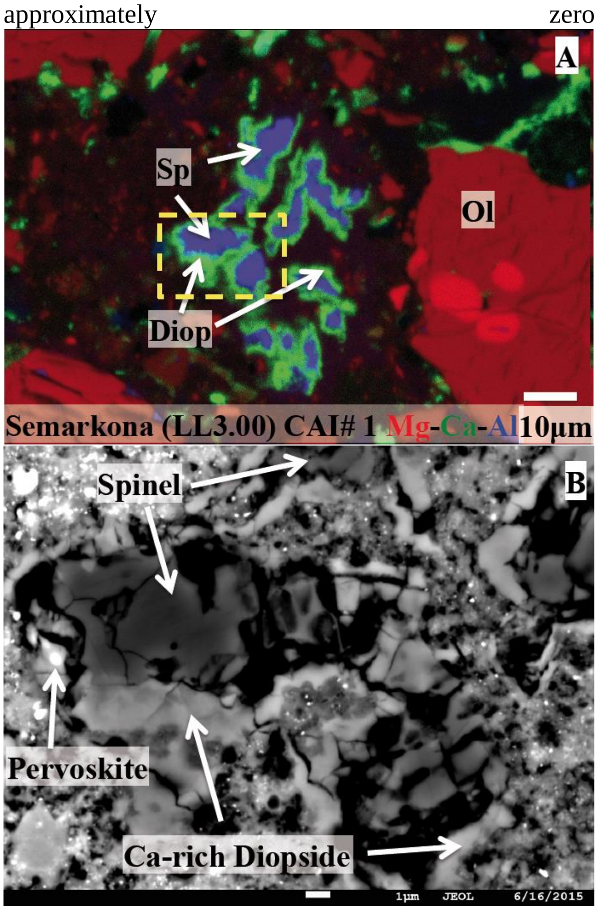
CAI#2: The inclusion is a ~140×115 μm fragment with fractured Ca-rich pyroxene surrounded by a fine grained matrix (Fig. 1 C). It is composed of several spinel grains (5-6) of varying sizes (5-12 μm) within the Ca, Al- rich pyroxene that paradoxically appear to be associated with neighboring orthopyroxene and olivine. The spinel grains are anhedral, zoned with rounded edges. Spinel grains have higher abundance of FeO of ~ 12 wt.%, similar to the olivine (~13.5 wt.%) nearby, compared to the surrounding pyroxene which have FeO of ~6-10 wt.%. The Ca-rich pyroxene is marginally zoned in FeO, and MgO compensating mostly for increasing Al_2O_3 towards the central region. TiO_2 content also increases from ~0.6 to 1.4 wt.% in the core of the pyroxene.

CAI#3: is ~188×138 μm spheroidal object that is an aggregrate of several nodules (Fig. 1 D). The inclusion is severely perforated but its margins are devoid of cracks/ breakage unlike the other two CAIs. It is mostly made up of pyroxene with regions with composition of Ca-rich (CaO~20-22 wt.%) diopside and minor anorthite. Some Fe-rich metal grains are also present within the nodules.

Discussion: Previous studies suggest that most of the CAIs found in ordinary chondrites are small (20-100μm; max size ~480μm) and altered to varying degrees. Specifically the two CAIs reported previously in Semarkona were hibonite-spinel-melilite bearing (1805-2-1) and type A (4128-3-1) of ~480μm and 320×130 μm, respectively [2-3]. So, the CAIs reported here are smaller than those, but larger than the average for ordinary chondrites and enhance the diversity of the mineralogy and morphology type found in Semarkona. The nodular aggregate forming chain-like inclusions have been previously reported in a carbonaceous chondrite (e.g., Mighei CM) [1]. and also recently observed by us in QUE 99177 (CR3.0) where a few of the nodules also have perovskite grains (unpublished).

Despite the pristine nature of Semarkona, the CAIs discovered herein show varying degrees of alteration evidenced by their abundance of FeO and Na_2O ranging from very low (<0.3 wt. %) to ~12-14 wt.% within spinel and pyroxene. Although texturally CAI#1, and #3

appear to be more mechanically fractured, the mineralogy suggests CAI#1 to have limited and least alteration, while CAI#2 appears to have been reprocessed/ altered significantly. Locally, the high abundances of FeO and Na_2O in regions of matrix surrounding the inclusions and yet the low and limited range within the inclusions themselves are consistent with the pristine low unequilibrated petrographic character of Semarkona. Furthermore the range of elemental distribution between CAIs suggests that the alterations of these inclusions may have occurred in the nebular environment prior to their accumulation in the Semarkona parent body. In order to futher evaluate the conditions in which the CAIs might have formed estimates of fO2 were determined following the approach of [8]. The calculated Ti^{3+}/Ti^{4+} of the pyroxene implement the methods refined by [9]. Representative EMPA pyroxene data from CAI#1 range from approximately zero



to 0.209±0.035 (2σ). Excess Ti^{3+} of some pyroxene in CAI#2 could be even larger up to 0.688±0.649 (2σ). The positive values imply formation in the purported reduced environment; the more common Ti^{3+} deficits likely mean the pyroxene and thus their host CAIs were either altered/reequilibratied on the Semarkona parent body or formed in a more oxidized environment.

Summary: Rare CAIs with diverse morphology and mineralogy showing varying degree of alteration within the least altered unequilibrated ordinary chondrite, Semarkona (LL3.00), have been found.

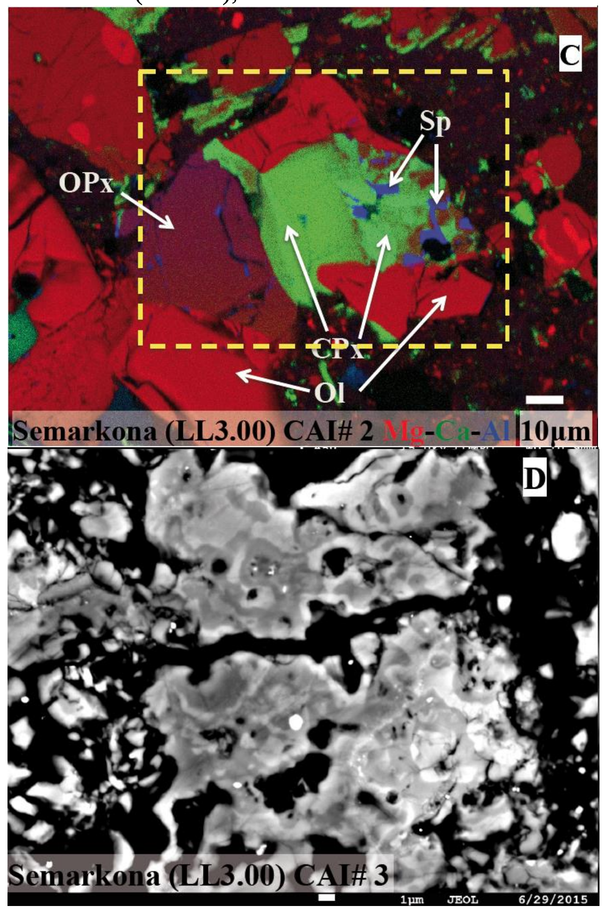


Fig. 1(A)Mg-Ca-Al (RGB) mosaic map of CAI#1; inset is shown in (B). (B) Magnified image of one of the nodules. Note the perovskite grain. Several sub to µm size Fe- rich grains are also seen in the surrounding matrix. (C) Mg-Ca-Al mosaic map of CAI#2 region, object of interest is the Ca, Al-rich (green colored) shown as the inset rectangle. (D) BSE image of one of the nodules of CAI #3.

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